

DINUCLEAR CONCEPT – CLUSTER MODEL OF FUSION

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The synthesis of superheavy elements is analysed within the dinuclear system concept of compound nucleus formation. The perspectives for using radioactive beams in complete fusion reactions are discussed.

The existing fusion models are distinguished by the choice of the relevant collective degree of freedom which is mainly responsible for the complete fusion. For example, many models assume a melting of the nuclei along the relative distance. It was demonstrated that the adiabatic scenario of fusion in the relative distance leads to an overestimation of the fusion probability P_{CN} ¹ and mostly gives an incorrect isotopic trend of P_{CN} . In the dinuclear system (DNS) concept² the compound nucleus is reached by a series of transfers of nucleons from the light nucleus to the heavy one. The dynamics of the DNS is considered as a combined diffusion in the degrees of freedom of the mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$ (A_1 and A_2 are the mass numbers the DNS nuclei) and of the relative distance describing the formation of the compound nucleus and the quasifission process (decay of the DNS), respectively³. The competition between the complete fusion and quasifission processes is taken into consideration in the DNS model and leads to a strong reduction of the fusion cross section^{3,4}. This cluster fusion model is justified by the structural forbiddenness effect⁵ which hinders the nuclei to melt together along the relative distance. In the DNS concept³ the evaporation residue cross section is calculated as $\sigma_{ER} = \sum_J \sigma_c P_{CN} W_{sur}$, where σ_c is the capture cross section for angular momentum J . The stabilizing shell effects of the formed superheavy compound nucleus against fission in the de-excitation process are thoroughly studied by the theory and surviving probabilities W_{sur} of compound nuclei are derived. The dependence of the probability of complete fusion P_{CN} on nuclear structure effects during the fusion process starting from the entrance channel and ending with the compound nucleus formation is the crucial factor for the correct calculation of σ_{ER} . In the reactions $^{90}\text{Zr} + ^{90,92,96}\text{Zr}$, $^{90,96}\text{Zr} + ^{100}\text{Mo}$, $^{86}\text{Kr} + ^{99,102,104}\text{Ru}$, $^{90,92,94,96}\text{Zr} + ^{124}\text{Sn}$ and $^{86}\text{Kr} + ^{130,136}\text{Xe}$ the fusion probabilities are decreased⁶ when the neutron number of projectile or target deviates from the magic number. In the DNS model this behaviour is simply

explained taking the deformation of nuclei and shell effects in dependence of the DNS potential energy on η into account. For example, the value of the energy threshold for fusion, which determines P_{CN} , is larger in the $^{86}\text{Kr}+^{130}\text{Xe}$ reaction than in the $^{86}\text{Kr}+^{136}\text{Xe}$ reaction. So, the values of P_{CN} and W_{sur} are larger in the reaction with ^{136}Xe than with ^{130}Xe , which leads to a difference of the about 3 orders of magnitude in σ_{ER} in these reactions. In the fusion reactions leading to actinides, for example the $^{66,76}\text{Zn}+^{174}\text{Yb}$ reaction, the increase of W_{sur} with increasing neutron number of the system is stronger than the decrease of P_{CN} . This gives evident benefit to the neutron-rich projectiles for producing actinides.

In contrast to other models, the optimal excitation energy E_{CN}^* of the compound nucleus formed in cold fusion reactions is reproduced in the DNS concept. The value of E_{CN}^* increases after $Z=113$ (Fig. 1a). The difference between the Q -values of Refs. ^{8,9} for elements till $Z=113$ is small. The strong decrease (few orders of magnitude) of the cold fusion cross section with increasing charge number Z of the compound nucleus ⁷ is mainly caused by a decrease of the fusion probability P_{CN} due to a strong competition between complete fusion and quasifission in the DNS (Fig. 1b). Therefore, in reactions $^{76,74}\text{Ge}+^{208}\text{Pb} \rightarrow ^{283,281}114+1n$ we expect a value of σ_{ER} which is smaller than 0.2 pb. The σ_{ER} for the $Z=116$ and 118 elements formed in the $^{80,82}\text{Se}, ^{84,86}\text{Kr}+^{208}\text{Pb}$ reactions are smaller than the value for $Z=114$. In actinide-based reactions $^{48}\text{Ca}+^{232}\text{Th}$, ^{238}U , $^{242,244}\text{Pu}$, ^{248}Cm , ^{249}Cf , the P_{CN} also decrease with increasing Z , but they are larger than in Pb-based reactions. For $^{48}\text{Ca}+^{244}\text{Pu} \rightarrow ^{289}114+3n$, the P_{CN} is 6×10^{-4} which is about 10^5 times larger than in $^{76}\text{Ge}+^{208}\text{Pb} \rightarrow ^{283}114+1n$. The gain in fusion and capture probabilities for actinide-based reactions with respect to cold fusion reactions is not compensated by loss in the survival probability of the compound nucleus. So, our comparison of the formation cross section of element $Z=114$ in Pb- and actinide-based reactions shows that the latter one is larger ($\sigma_{3n}=1.5$ pb) ⁴. The σ_{ER} of the $^{48}\text{Ca}+^{248}\text{Cm}, ^{249}\text{Cf}$ reactions are smaller than experimental $\sigma_{ER}=1$ pb of the $^{48}\text{Ca}+^{244}\text{Pu}$ reaction.

In the Pb-based reactions with neutron-rich nuclei $^{70,74,78}\text{Ni}$, ^{80}Zn , ^{86}Ge and ^{92}Se the increase of W_{sur} with the number of neutrons could be compensated by decreasing P_{CN} . For example, in the $^{62}\text{Ni}+^{208}\text{Pb}$ reaction the yield of the $Z=110$ element is comparable with the yields in the $^{70,74}\text{Ni}+^{208}\text{Pb}$ reactions. The larger lifetime of the neutron-rich superheavies will allow a detailed study of their properties.

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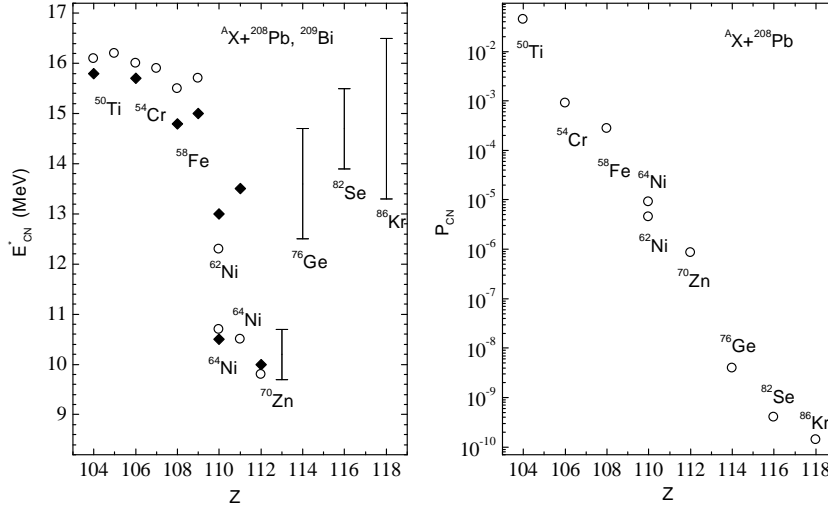


Figure 1: a) Optimal excitation energies of the compound nuclei. b) Calculated fusion probabilities P_{CN} for cold fusion (HI,1n) reactions. The experimental data⁷ are shown by solid diamonds. The projectiles are indicated. For compound nuclei with $Z=104-112$, the calculations were performed with Q -values from Ref.⁸. For the elements with $Z \geq 113$ the lower (upper) limit of bars was calculated with Q -values from Ref.⁸ (Ref.⁹).

References

1. G.G.Adamian et al., *Nucl. Phys. A* **646**, 29 (1999).
2. V.V.Volkov, *Izv. AN SSSR ser. fiz.* **50**, 1879 (1986).
3. N.V.Antonenko et al., *Phys. Lett. B* **319**, 425 (1993); *Phys. Rev. C* **51**, 2635 (1995); G.G.Adamian et al., *Nucl. Phys. A* **618**, 176 (1997); **A** 627, 332 (1997); **A** 633, 154 (1998); R.V.Jolos et al., *Europ.Phys.J. A* **4**, 245 (1999).
4. E.A.Cherepanov, *Pramana* **23**, 1c (1999); Yu.Ts.Oganessian et al., Preprint JINR, E7-99-53 (1998).
5. G.G.Adamian et al., *Phys. Lett. B* **451**, 289 (1999).
6. K.H.Schmidt, W.Morawek, *Rep. Prog. Phys.* **54**, 949 (1991).
7. S.Hofmann, *Rep. Prog. Phys.* **61**, 570 (1998); G.Münzenberg *Phil. Trans. R. Soc. Lond. A* **356**, 2083 (1998).
8. P.Möller, J.R.Nix, *At. Data Nucl. Data Tables* **39**, 213 (1988).
9. P.Möller et al., *At. Data Nucl. Data Tables* **59**, 185 (1995).